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EFFECTS OF NEGATIVELY CHARGED MASSIVE PARTICLES ON PRIMORDIAL STARS

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ABSTRACT

The effects of negatively charged non–strongly interacting massive particles, denoted as X^- particles, on stellar hot hydrogen burning are considered. Such particles would bind to nuclei and catalyze a very efficient hydrogen-burning cycle. This nuclear burning cycle would occur because the additional binding energy provided by binding the X^- particles to ^{8}Be nuclei creates a stable entity. Although such a cycle would not be likely to be of significance to present-day stars, it could significantly alter the range of masses for which primordial Population III stars explode. The nucleosynthesis produced in these X^--induced supernovae can differ markedly from that of ordinary β-limited CNO cycle–induced explosions of very massive and supermassive stars. Thus the resulting abundances might provide constraints on the existence of intermediate lifetime X^- particles and/or the Population III initial mass function.

Subject headings: elementary particles — stars: abundances — stars: interiors

1. INTRODUCTION

There has been considerable speculation on the role of hypothetical charged massive particles in cosmology (Dimopoulos et al. 1990; Fukugita, Hut, & Spergel 1990; Chivukula & Walker 1990; and DeRujula, Glashow, & Sarid 1990). An example of such a particle might be the supersymmetric counterpart of a lepton, suggested by supersymmetric theories (cf. Kane 1984). Despite the theoretical effort which supports the idea of hypothetical charged massive particles, these particles remain unobserved, and, in fact, astrophysical constraints show they could not be the dark matter if their masses are less than 10^3 TeV (Dimopoulos et al. 1990). They could, however, exist in smaller abundances over appreciable ranges in mass, lifetime, and interaction strength. Many of the basic properties of these particles have been discussed previously (Boyd et al. 1989, hereafter BTPM). As in that study, we confine our discussion to X^- particles which are considerably more massive than a nucleon (searches for many possible varieties of them preclude many such possibilities for masses below about 50 GeV; cf. Akrawy et al. 1990), negatively charged, and not participating in the strong interaction. We emphasize that we are not assuming a closure density in the present study; indeed, we are interested in X^- densities well below that. This is, in fact, the parameter space of X^- particle characteristics which has been most difficult to constrain. We have also assumed that the spin of the X^- is zero; a nonzero value would modify the results of our considerations of nuclear decays.

In BTPM it was argued that two searches, one in hydrogen (Smith & Bennett 1979; Smith et al. 1982) and the other in boron (Hemmick et al. 1990), suggest that X^- do not exist in the present galaxy at an abundance level of about 1×10^{-25} per nucleon over a fairly wide mass range. We will assume this to be the present-day upper limit for their abundance. This limit of itself is sufficient to preclude X^- from having a significant effect on present generation stars. Such possible effects were investigated by Boyd et al. (1985), who assumed generic nuclei which would efficiently catalyze H-burning. They concluded that an abundance of one such nucleus per 10^{15} normal nuclei would be required to have much of an impact on stellar burning. However, X^- would be less efficient as a catalyst than the generic nuclei discussed by Boyd et al. (1985). Thus the present experimental limits on the abundance of X^- would have to be relaxed by many orders of magnitude for them to be significant to stellar burning in present-day stars. Accordingly we have sought signatures for their existence in primordial stars.

Even though X^- particles may have a small abundance, they could have a dramatic effect by catalyzing H-burning in massive first-generation stars. The general approach of Boyd et al. (1985) can be applied to constrain X^- properties and abundances from their catalytic effect on nuclear hydrogen burning and the concommitant changes in nucleosynthesis in massive objects exploding from high temperatures which would result from their presence. Such very massive and supermassive objects (Wagoner, Fowler, & Hoyle 1967; Fricke 1973, 1974; Iben 1963; Norgaard & Fricke 1976; Carr, Bond, & Arnett 1981; and Fuller, Woosley, & Weaver 1986) have previously been discussed in connection with a possible "Population III," or primordial, generation of stars, the nucleosynthesis from which might explain the floor on the mass fraction of intermediate and heavy-mass elements ($X_{heavy} > 10^{-10}$) observed in old Population II halo stars. Though the initial mass function (especially for very massive stars), star formation rate, epoch of formation, and in fact the existence or nonexistence of Population III stars remain problematic, we note that, at least in principle, the nucleosynthesis from such stars may be constrained by observations coupled with successful models of Galactic chemical evolution (cf. Carr et al. 1981). We will point out that over broad ranges in X^- mass and lifetime they will have the effect of extending the explosion boundary for massive stars to lower metallicities. In turn these explosions may give a nucelosynthesis yield which is in principle amenable

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to observational constraint. In effect the resulting constraint would be on some combination of X^- abundance coupled with the primordial initial mass function (IMF) and star formation rate.

In studying the effects of X^- particles on first-generation stars, we required estimates of thermonuclear reaction rates and β-decay lifetimes. The reaction rates were estimated by combining general prescriptions from nuclear astrophysics with detailed nuclear structure information. The β-decay lifetime estimates relied on well-known nuclear systematics. Inherent in the study of primordial stars are the predicted abundances of CNO nuclides from big bang nucleosynthesis; these are far too small for them to catalyze H-burning in first-generation stars. Other assumptions associated with primordial stars are the standard ones and are discussed in the literature on that subject.

In § 2 we discuss the nucleosynthesis cycles involving nuclei with embedded X^- particles which would occur in Population III stars and discuss the estimates we have made for reaction rates and lifetimes of such X^--nuclides. Section 3 presents our arguments concerning nucleosynthesis in massive primordial stars. Finally, § 4 summarizes our conclusions.

2. NUCLEOSYNTHESIS INVOLVING NUCLEI WITH EMBEDDED X^- PARTICLES

Some of the properties required of X^- particles noted by BTPM (1989) are important to the present study and so will be reviewed here. As noted above, high-energy physics experiments have shown that many candidates for X^- particles must, if they exist at all, have a mass in excess of about 50 amu. Our conclusions, however, would not be altered appreciably for X^- masses as low as a few nucleon masses. We follow BTPM (1989) and assume that X^- have only electromagnetic interactions in nuclei. Such particles would be bound to nuclei with binding energies typically of the order of MeV (except for hydrogen and helium nuclei), and would have orbital sizes smaller, except for the lightest nuclides, than the size of the nuclei. The binding energy of an X^- to a proton would only be 25 keV, so that system would be ionized even at fairly low stellar temperatures (T). However, the binding energies for all other nuclides would be large enough that, unless the stellar T became quite high ($T_6 > 150$ for He, considerably higher for all heavier X^--nuclides), the X^- would remain bound to the nucleus.

Nuclei having bound X^- particles can catalyze hydrogen burning via the cycles shown in Figure 1. (It should be noted that the reactions in the lower mass cycle are similar, but not identical, to those discussed by Turkevich, Weilgoz, & Economou 1984. Their reaction cycle, however, applies to a lower T environment than would that shown in Fig. 1.) The sequence of reactions indicated in Figure 1, denoted as the He^{x}Be^{x}B^{x}C^x cycle, will proceed rather quickly, due to the low Coulomb barriers of the associated nuclei. The cycle proceeds by first forming ^{8}Be^x via capture of a ^{4}He^x by a ^{4}He nucleus which, due to the neutralization of one unit of charge of the ^{4}He by the bound X^- particle, has a Coulomb barrier like the p-^{4}He system. thus this reaction proceeds very rapidly even at low stellar T; its reaction rate estimated assuming a direct capture (nonresonant) mechanism is indicated in Figure 2. Since resonant effects would only increase that reaction rate, this estimate thus serves more as a lower limit on that rate than an estimate of it. As noted in BTPM the additional binding energy

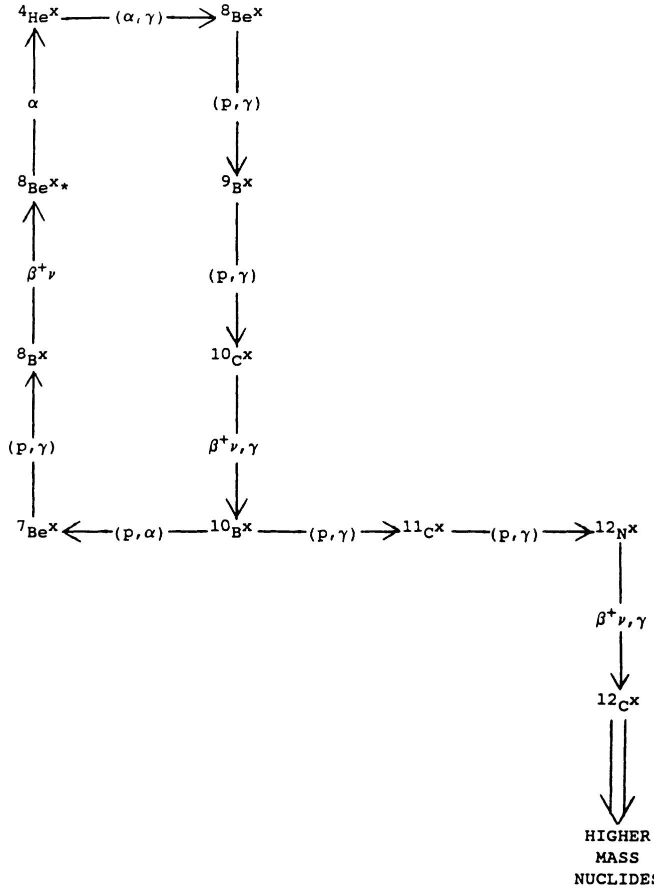

FIG. 1.—Energy-generating cycle via hydrogen burning of X^- nuclides. Note that ^{8}Be^x is stable, making possible the high efficiency of this cycle.

given to ^{8}Be^x by the bound X^-, 1.62 MeV produces a stable "nucleus", even though ^{8}Be without the bound X^- decays into two ^{4}He nuclei with an extremely short half-life. At $T_6 >$ 150, the X^- in the ^{4}He^x could be readily ionized (BTPM) from the ^{4}He, reducing its usefulness as a catalyst for H-burning above that T.

Once ^{8}Be^x is formed, two (p, γ) reactions would convert the ^{8}Be^x to ^{10}C^x. Note that the ^{8}Be^x(p, γ) reaction would not, if performed on normal nuclei, have a positive Q-value, so would not proceed. However, the effect of the bound X^- is again sufficient to produce a positive Q-value. Once ^{10}C^x is reached, however, the He^{x}Be^{x}B^{x}C^x cycle must pause, as capture of another proton is not energetically allowed; this cycle is thus "β-limited." However, the nucleosynthesis paths can branch in an important way at ^{10}C^x; once ^{10}C^x has β-decayed to ^{10}B^x (actually to its first excited state, which immediately decays to the ground state), with an estimated half-life of 120 s, the He^{x}Be^{x}B^{x}C^x cycle can be continued by a ^{10}B^x(p, γ)^{7}Be^x reaction. However, from ^{10}B^x (see Fig. 1), two more (p, γ) reactions together with two more β-decays could boost the X^- nuclides to ^{12}C^x and hence into a cycle (see Fig. 3) involving C^x, N^x, and O^x. If the ^{10}B^x(p, α)^{7}Be^x reaction occurs, it will be followed by a ^{7}Be^x(p, γ)^{8}B^x reaction. ^{8}B^x would β-decay to the ^{8}Be^x first excited state, which would quickly break up into ^{4}He and ^{4}He^x, completing the cycle. Other potential reaction paths in this cycle are found not to be energetically allowed when the binding energies of the X^- particles are taken into account.

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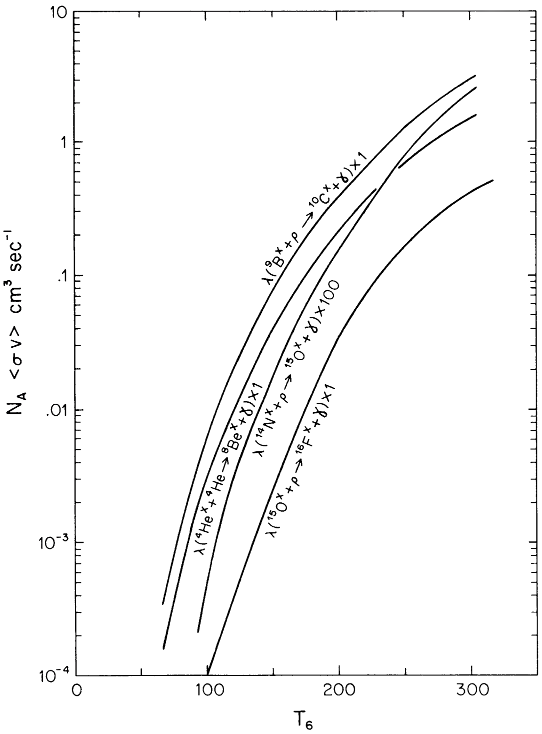

FIG. 2.—Reaction rates for various processes for X^- nuclides. Direct capture reactions were assumed except for $^{15}O^x(p, \gamma)^{16}F^x$, for which a resonance capture mechanism was used. The hydrogen density was assumed to be 1 g cm^{-3} for these rates.

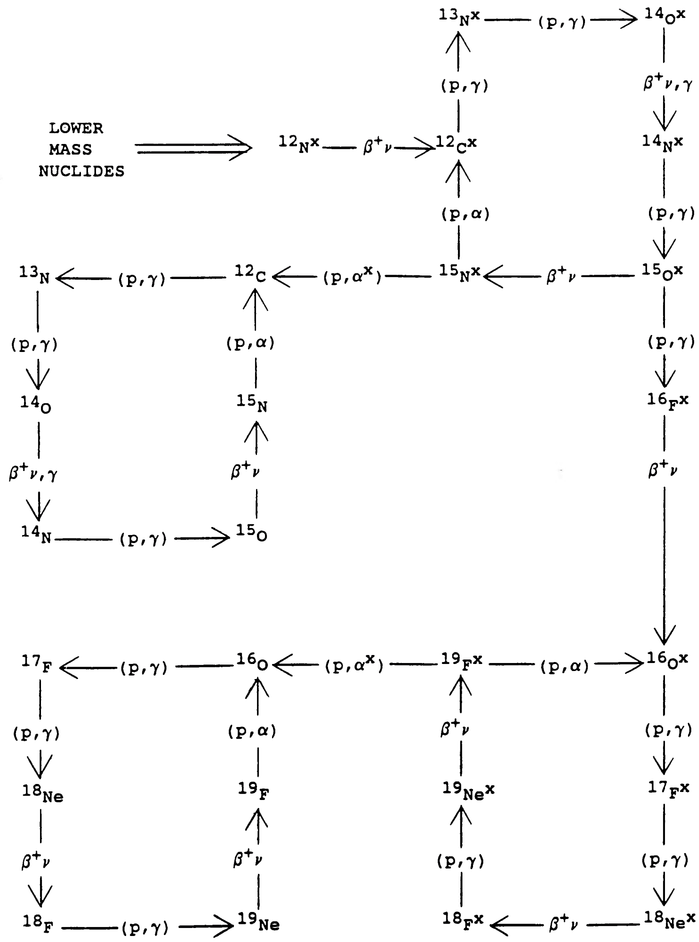

FIG. 3.—Higher mass cycles for X^- nuclides in hydrogen-burning. Note that two of the cycles involve X^- nuclides, while two of them involve normal nuclides.

At fairly high T, the rate for this cycle would be limited by the half-life of $^{10}C^x$; it thus would proceed approximately every 120 s to convert four protons into a ^{4}He nucleus. This conclusion is based on comparison of the reaction rates for the reactions within the cycle; those for $^4He^x(^4He, \gamma)^8Be^x$ (taken from BTPM) and $^9B^x(p, \gamma)^{10}C^x$ (see discussion of calculation of these rates) are shown in Figure 2.

As noted above, once $^{10}C^x$, has decayed to $^{10}B^x$, the $^{10}B^x(p, \gamma)^{11}C$ and $^{11}C^x(p, \gamma)^{12}N^x$ reactions could also occur, producing, after another β-decay, $^{12}C^x$ and, hence, leakage of the X^--nuclides from the He^{x}Be^{x}B^{x}C^x cycle into the "C^{x}N^{x}O^x cycle". This latter cycle, assuming a sufficiently high T that the C^{x}N^{x}O^x reactions would proceed rapidly (they would again be aided, compared to the reactions involving the corresponding normal nuclei, by the reduction in the Coulomb barrier resulting from the bound X^-), would be β-limited at $^{14}O^x$. After the β-decay of $^{14}O^x$ to the first excited state of $^{14}N^x$, γ-decay to the $^{14}N^x$ ground state, a (p, γ) reaction to $^{15}O^x$, another β-decay to $^{15}N^x$, and finally a $^{15}N^x(p, \alpha)^{12}C^x$ reaction, the C^{x}N^{x}O^x cycle returns to its $^{12}C^x$ catalyst. Note, however, that this cycle does have a possible branch at $^{15}N^x$: either the $^{15}N^x(p, \alpha)^{12}C^x$ reaction or the $^{15}N^x(p, \alpha^x)^{12}C$ reaction can occur. In the former case the C^{x}N^{x}O^x cycle is continued. In the latter, however, normal ^{12}C is formed, and the resulting $^4He^x$ returns to catalyze the He^{x}Be^{x}B^{x}C^x cycle. Then both the He^x and the newly formed ^{12}C will catalyze subsequent H-burning! The limiting reaction rate for the C^{x}N^{x}O^x cycle is that expected to be the slowest in the cycle, namely $^{14}N^x(p, \gamma)^{15}O^x$; it is indicated in Figure 2. If T is sufficiently high, however ($T_6 > 200$ would be required at a density of 1 g cm^{-3}), this cycle would be β-limited, so would produce an ^{4}He nucleus out of four protons roughly every 1000 s.

As with the He^{x}Be^{x}B^{x}C^x cycle, leakage from the C^{x}N^{x}O^x cycle, primarily from the $^{15}O^x(p, \gamma)^{16}F^x$ reaction would occur (see Fig. 1). This reaction, the estimated rate for which is also shown in Figure 2, could not occur without the additional binding energy of the X^-. However, because of the long (740 s) half-life of $^{15}O^x$ into the next highest mass cycle, that involving O^x, F^x, and Ne^x, a reasonable fraction of the time. At T_6 of 150, this would be expected to occur most of the time, based on the estimated reaction rate for this reaction (see below). Once $^{16}F^x$ has been formed and has β-decayed to $^{16}O^x$, an H-burning cycle involving O^x, F^x, and Ne^x (see Fig. 3) would occur. At the upper end of this cycle, a $^{19}Ne^x(p, \gamma)^{20}Na^x$ reaction would cause some leakage from this cycle, but the reaction rates at T values characteristic of very massive and supermassive Population III stars will inhibit very much such leakage. Instead, $^{19}Ne^x$ would almost always β-decay to $^{19}F^x$, at which point (see Fig. 3) either the $^{19}F^x(p, \alpha)^{16}O^x$ or the $^{19}F^x(p, \alpha^x)^{16}O$ reaction would occur, the latter one making ordinary ^{16}O as the C^{x}N^{x}O^x cycle made ordinary ^{12}C.

The β-decays which dominate these two cycles were determined by correcting the decay Q-values for the presence of the X^- (see the binding energy values given in Table 1), then

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TABLE 1

Q-VALUES AND IMPORTANT HALF-LIVES OF X^--CATALYZED PROCESSES

Reaction	Q-Value (MeV)	Half-Life (s)
$^4He^x(^4He, \gamma)^8Be^x$	1.08	
$^8Be^x(p, \gamma)^9B^x$	0.50	
$^9B^x(p, \gamma)^{10}C^x$	4.66	
$^{10}C^x \rightarrow {}^{10}B^x(0.72) + \beta^+ + \nu$	2.27	120
$^{10}B^x(p, \alpha)^7Be^x$	0.47	
$^7Be^x(p, \gamma)^8B^x$	0.82	
$^8B^x \rightarrow {}^8Be^x(3.04) + \beta^+ + \nu$	14.26	<1
$^8Be^x(3.04) \rightarrow {}^4He^x + {}^4He$	1.87	<1
$^{10}B^x(p, \gamma)^{11}C^x$	9.35	
$^{11}C(p, \gamma)^{12}N^x$	1.23	
$^{12}N^x \rightarrow {}^{12}C^x + \beta^+ + \nu$	16.71	<1
$^{12}C^x(p, \gamma)^{13}N^x$	2.57	
$^{13}N^x(p, \gamma)^{14}O^x$	5.23	
$^{14}O^x \rightarrow {}^{14}N^x(2.31) + \beta^+ + \nu$	2.23	
$^{14}N^x(p, \gamma)^{15}O^x$	7.90	
$^{15}O^x \rightarrow {}^{15}N^x + \beta^+ + \nu$	2.16	740
$^{15}N^x(p, \alpha)^{12}C^x$	4.34	
$^{15}N^x(p, \alpha^x)^{12}C$	1.77	
$^{15}O^x(p, \gamma)^{16}F^x$	0.03	
$^{16}F^x \rightarrow {}^{16}O(7.12) + \beta^+ + \nu$	7.74	
$^{16}O^x(p, \gamma)^{17}F^x$	1.16	
$^{17}F^x \rightarrow {}^{17}O^x + \beta^+ + \nu$	2.20	
$^{17}O^x(p, \alpha)^{14}N^x$	0.62	
$^{17}O^x(p, \gamma)^{18}F^x$	6.17	
$^{18}F^x(p, \gamma)^{19}Ne^x$	6.93	
$^{19}Ne^x \rightarrow {}^{19}F^x + \beta^+ + \nu$	2.72	55
$^{19}F^x(p, \alpha)^{16}O^x$	9.93	
$^{19}F^x(p, \alpha^x)^{16}O$	6.17	

adjusting the half-lives, using the f-value tables of Gove & Martin (1971), according to the equation

$$T_{1/2}{}^x/T_{1/2}{}^N = f^N/f^x . \quad (1)$$

This expression results from the assumption that the fT values, which depend on the structure of the nucleus involved, would be the same for the X^- nucleus as for the normal (N) nucleus. Since we are dealing with light nuclei, the level spacing is large compared to net energy shifts due to the X^- binding energy, so no extra β-branches will contribute.

The reaction rates per constituent pair were estimated for all reactions except $^{15}O^x(p, \gamma)^{16}F^x$ by assuming the standard expression for such rates (Rolfs & Rodney 1988)

$$\langle \sigma v \rangle = 7.2 \times 10^{-19} \tau^2 e^{-\tau} s/(AZ_1Z_2) \quad (\mathrm{cm^3\ s^{-1}}) \quad (2)$$

where

$$\tau = 42.46(Z_1^2 Z_2^2 A/T_6)^{1/3} , \quad (3)$$

Z_1 and Z_2 are the charge numbers of the two interacting nuclei, and A is their reduced mass in atomic mass units. For (p, γ) reactions, S, the astrophysical S-factor, was taken to be 1.0 keV barn, a typical value (Rolfs & Rodney 1988) for proton radiative capture reactions. The resulting rates are shown in Figure 2. As noted above, the rates estimated in this way are nonresonant rates; they therefore represent lower limits on such rates rather than accurate estimates. Actual rates for X^- nuclei would most likely be greater than those indicated in Table 1 [except that for $^{15}O^x(p, \gamma)^{16}F^x$], possibly by one or two orders of magnitude if the relevant compound nuclei had resonances close to the Gamow window.

A case in point is provided by the $^{15}O^x(p, \gamma)^{16}F^x$ reaction which, because it is critical to our conclusions, was examined in detail. The Gamow window for this reaction would be expected to be at about 126 keV at $T_6 = 150$. The ground state of $^{16}F^x$ is estimated (see Table 1) to be bound by 30 keV, placing the first excited state (Sterrenberg et al. 1984) at 160 keV, very close to the Gamow window. Thus a resonant reaction rate estimate must be used for this reaction. This is given (Rolfs & Rodney 1988) by

$$\langle \sigma v \rangle = 8.09 \times 10^{-12} (\omega\gamma)_3 A^{-3/2} T_6^{-3/2} \exp(-11.605\, E_3/T_6) , \quad (4)$$

where $(\omega\gamma)_3$ is the usual statistical factor times resonance width with the resonance partial width in keV, and E_3 is the resonance energy in keV, 160 for this case. The value of $(\omega\gamma)_3$ can be estimated (Preston 1962) to be 2.2×10^{-7} keV for the $J^\pi = 1^-$ resonance associated with the first excited state of $^{16}F^x$. This estimate assumed a magnetic dipole transition to the $J^\pi = 0^-$ ground state and a narrow resonance. It also assumed both ground and first excited states to be dominated by configurations consisting of a $2s_{1/2}$ proton and a $1p_{1/2}$ neutron hole, an assumption which is experimentally confirmed (Bohne et al. 1973). Although the width of the ^{16}F (first excited state) has been found to be about 100 keV (Sterrenberg et al. 1984), the width of the corresponding state in $^{16}F^x$ would be expected to be much less, due to the reduction in proton width resulting from the lower proton energy in $^{16}F^x$. This justifies the use of the narrow resonance formula.

The calculated rate is shown in Figure 2; it is roughly 100 times as large as that for nonresonant capture, increasing to more than 200 times at $T_6 = 150$.

Comparison of the reaction rates for $^{10}B^x(p, \gamma)^{11}C^x$ and $^{10}B^x(p, \alpha)^7Be^x$ determines the relative amounts of X^- catalyzed fusion in the upper two cycles to that in the lower energy-generating cycle at any stellar T. Thus some estimate of their values is important to understanding the nucleosynthesis of exploding Population III stars. While this is difficult to do in detail, since it might well depend on resonances about which we have little or no information, (p, α) reactions generally dominate over (p, γ) reactions by several orders of magnitude. Even this much leakage would, however, produce a significant number of nuclides heavier than $^{12}C^x$ in primordial stars.

The relative amounts of C and O in metal-poor stars appear to be weighted strongly toward O in metal-poor stars (Andreani, Vangione-Flam, & Audouze 1988; Clegg, Lambert, & Thompkin 1981). Since X^- particles might have been considerably more abundant soon after the big bang than they are now, it is of interest to predict the O-to-C abundance ratio which might result from X^- catalyzed nucleosynthesis. One important ratio, denoted as R_{decay}, is that of the rate for production of ^{16}F compared to the rate for decay of $^{15}O^x$ to $^{15}N^x$, since ^{16}O is made by the cycle initiated by the $^{15}O^x(p, \gamma)^{16}F^x$ reaction, and ^{12}C is made by the $^{15}N^x(p, \alpha^x)^{12}C$ reaction. Two other ratios of importance are R_{12}, that of the rate for $^{15}N^x(p, \alpha^x)^{12}C$ to $^{15}N^x(p, \alpha)^{12}C^x$, and R_{16}, that of the rate for $^{19}F^x(p, \alpha^x)^{16}O$ to $^{19}F^x(p, \alpha)^{16}O^x$. If it is assumed that each $^{12}C^x$ nucleus made will complete enough processing cycles to end up ultimately in either the lower mass cycle, i.e., as C or N, or the upper mass cycle, i.e., as O or F, then it can be seen that the abundance ratio at O and F to C and N Pr(O, F/C, N) produced in these cycles will be

$$\mathrm{Pr(O, F/C, N)} = R_{\mathrm{decay}}(1 + R_{12}^{-1}) . \quad (5)$$

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If it is assumed that sufficient processing time occurs, then R_{16} does not enter this equation explicitly. However, it must be large enough that too large a processing time is not required.

We have estimated $R_{\rm decay}$ from the estimated half-life of $^{15}O^x$ of 740 seconds and the reaction rate estimated for $^{15}O^x(p, \gamma)^{16}F^x$. This rate as a function of T is shown in Figure 3: it gives $R_{\rm decay} = 2.7$ at $T_6 = 150$ and a density of 1 g cm^{-3} (parameters typical of very massive and supermassive stars). If it is assumed that the X^- does not affect the nuclear structure in the (p, α) reactions, then two factors are required to estimate R_{12} and R_{16}. The first involves phase space. The reaction rates will be proportional to the density of final states dN/dE, which goes as

$$dN/dE \propto m^{3/2}E^{1/2} \tag{6}$$

for nonrelativistic particles in a potential well. In equation (6), m is the reduced mass of the system and E is the center-of-mass energy in the final state. For the (p, α) reactions we are considering, the residual X^--nucleus will be much more massive than the α-particle, so the reduced mass is essentially that of the α-particle. For the (p, α^x) reaction, assuming the X^- is very massive, the reduced mass will be essentially that of the residual nucleus, ^{12}C or ^{16}O. Thus the $m^{3/2}$ factor favors $^{15}N^x(p, \alpha^x)$ to $^{15}N^x(p, \alpha)$ by a factor of 5.2 and $^{19}F^x(p, \alpha^x)$ to $^{19}F^x(p, \alpha)$ by a factor of 8.0. The $E^{1/2}$ factor is determined by the Q-values for the various reactions (see Table 1); it favors $^{15}N^x(p, \alpha)$ to $^{15}N^x(p, \alpha^x)$ by a factor of 1.56 and $^{19}F^x(p, \alpha)$ to $^{19}F^x(p, \alpha^x)$ by a factor of 1.41.

The second adjustment involves the barrier penetrability of the outgoing α or α^x particles. The penetrability is given by

$$P = \left\{\frac{E_C}{E}\right\}^{1/2} \exp\left\{\frac{4Z_1Z_2e^2}{hv}\left[-\frac{\pi}{2} + \sin^{-1}\left(\frac{E}{E_C}\right)^{1/2} + \left(\frac{E}{E_C}\right)^{1/2}\left(1 - \frac{E}{E_C}\right)^{1/2}\right]\right\}, \tag{7}$$

where E_C is the height of the Coulomb barrier at the nuclear surface (assumed to be $Z_1Z_2e^2/(1.2A^{1/3})$, A is the mass number of the residual nucleus (taken to be 12 for either C or C^x), and Z_1 and Z_2 are the charge numbers of the two particles involved. This expression is valid for zero angular momentum cases (which would be the case for the exit channel with which we are dealing here). Since both $^{19}F^x(p, \alpha)^{16}F^x$ and $^{19}F^x(p, \alpha^x)^{16}O$ are quite exothermic, this correction will have little effect on R_{16}. However, the effect on R_{12} is quite large. The penetrability adjustment favors $^{15}N^x(p, \alpha)^{12}C^x$ over $^{15}N^x(p, \alpha^x)^{12}C$ by a factor of 6.6. Thus $R_{16} = 0.85$ and $R_{12} = 0.33$.

Putting these factors together allows the prediction that O and F are produced about 8 times as frequently as are C and N at $T_6 = 150$, a characteristic T for massive stars. Note also that the "O + F" would be primarily ^{16}O, ^{17}O, and ^{18}O, since ^{19}F would be destroyed quickly by the $^{19}F(p, a)$ reaction, while the "C + N" would be primarily ^{14}N, since it would be expected to be the nuclide most slowly destroyed in hot hydrogen burning. Thus it appears that Population III stars with X^- particles could explain the relatively high O abundance observed in first-generation stars. Furthermore, this prediction does not appear to be very sensitive to the effects considered; it is difficult to circumvent the prediction of excess O compared to C and/or N. Note that one reaction not considered above which could distort this ratio, $^{17}O^x(p, \alpha)^{14}N^x$, does not do so. At T values typical of massive primordial stars, the $^{17}O(p, \alpha)$ and $^{17}O(p, \gamma)$ rates are very nearly equal, so continuation of the O, F, Ne cycle is just about as probable as return to the CNO cycle. However, the reduction in Q-value in the (p, α) reaction resulting from the bound X^- reduces the barrier penetrability for the outgoing α-particle by a factor of 300 for the $^{17}O^x(p, \alpha)^{14}N^x$ reaction compared to that for $^{17}O(p, \alpha)^{14}N$. Thus this reaction is not likely to have much effect on the Pr(O, F/C, N) value.

Another interesting prediction arises from this O production as a result of X^--catalyzed H-burning. The O isotopes will be the ultimate decay products of the 16, 17, and 18 baryon nuclides produced in the O, F, Ne cycle, but they would be ^{16}O, ^{17}O, or ^{17}F, and ^{18}F when they react with the protons in their radiative capture reactions. Thus one would expect the reaction rates, aside from resonances, on ^{16}O and ^{17}O to be comparable, but that for ^{18}F to be slower by roughly an order of magnitude, due to the increased Coulomb barrier for p + F over that of p + O. This would translate to comparable abundances for ^{16}O and ^{17}O, and a significantly larger abundance for ^{18}O for the nuclides produced in X^--catalyzed H-burning. This result is in marked contrast to the solar abundances, which have ^{16}O with a larger abundance than either of the other two nuclides by a factor of 500. The basic reason for these different abundances in the O isotopes in X^--catalyzed hydrogen-burning from the solar abundances is that ^{16}O is produced copiously in helium-burning. If some scenario existed by which ^{16}O could be produced very early in the universe, then included in hot hydrogen-burning in primordial stars (Wallace & Woosley 1981), the O isotopic abundances predicted for X^{-1}-catalyzed hydrogen-burning might be stimulated by normal nuclei. However, we know of no such scenarios, apart from inhomogeneous cosmologies, which predict extremely small O abundances (Kajino, Mathews, & Fuller 1990). The O isotopic abundances of very metal-poor stars thus comprise, at least in principle, a test of the possibility that moderately long-lived X^- particles could have been responsible for some nucleosynthesis in primordial stars.

3. NUCLEOSYNTHESIS IN MASSIVE PRIMORDIAL STARS

The primordial stars which are most effective in producing energy in the early universe may be very massive ($M > 100$ $M_\odot$) and supermassive ($M > 10^4$ $M_\odot$) objects (cf. review by Carr et al. 1984). Without getting into the controversial details of VMO and SMO evolution, it suffices to say that the nucleosynthesis from these objects is uncertain on several counts. First, we do not know how much of the baryonic mass of the universe is processed through these objects. Second, there remain uncertainties in the evolution of these objects. Notably, whether or not VMOs explode or collapse to black holes (carrying all of their interesting nucleosynthetic ash to oblivion) seems to depend sensitively on the interplay of rotation and nuclear burning (Stringfellow & Woosley 1988). In SMOs the situation is a little clearer: unless they have a metallicity in excess of $Z > 5 \times 10^{-3}$ (a very large metallicity by early universe standards, where we expect $Z < 10^{-10}$), they will not explode and will instead collapse to black holes (Fuller et al. 1986, hereafter FWW).

In any case, FWW found that low-metallicity SMOs that do explode do so on the β-limited CNO cycle, so that essentially their only nucleosynthesis product is ^{4}He. Combinations of rotation and/or new nuclear reaction rates may allow these stars to break out of the β-limited CNO cycle and produce small amounts of intermediate-mass elements in the rp-process

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(Wallace & Woosley 1981). But the $Z > 5 \times 10^{-3}$ metallicity cutoff indicates that primordial SMOs could not significantly affect abundances of the light- or intermediate-mass elements.

It would be very significant if the X^- catalysis scenario for hot H-burning discussed in the last section could extend the lower limit on metallicity required for SMO explosions to near zero, for in this case even a small amount of the baryonic mass going into SMOs could give a potentially interesting signature for X^--catalyzed nucleosynthesis. In fact we think this is the case because even for primordial abundances of C, N, and O a sufficiently large X^- concentration can effect an appreciable nuclear energy generation rate through the $\mathrm{He}^x\mathrm{Be}^x\mathrm{B}^x\mathrm{C}^x$ cycle. This large energy production rate allows the star to avoid the trap of having to collapse to high enough density for the triple-α reaction to produce enough ^{12}C to drive efficient CNO-cycle energy generation. If the star hangs up on $3\alpha \rightarrow {}^{12}\mathrm{C}$ production, then the infall kinetic energy built up in collapse exceeds the potential nuclear energy production, ensuring collapse to a black hole. This is the collapse-cook-collapse scenario discussed in FWW.

To see how large the X^- mass fraction must be in order to circumvent the collapse-cook-collapse scenario and affect an explosion in an SMO at very low metallicity we compare the time scale to burn hydrogen in the X^- cycle with that in the β-limited CNO cycle. The slowest rate in the X^- cycle is the positron decay

$$^{10}\mathrm{C}^x \rightarrow {}^{10}\mathrm{B}^x + \beta^+ + \nu ,$$

which has an estimated half-life of 120 s (see Table 1). In the β-limited CNO cycle at the conditions relevant to the onset of gravitational instability in SMOs ($T > 10^8$ K, $\rho \approx 1$ g cm^{-3}), the limiting rate is actually that for $^{14}\mathrm{N}(p, \gamma)^{15}\mathrm{O}$, which has an inverse rate (Fowler, Caughlan, & Zimmerman 1967) of about 8000 s per ^{14}N nucleus. If the number abundance fraction of ^{14}N reflects the lower limit $Z_{\mathrm{lim}}/\mathrm{H} < 10^{-6}$ for explosions in non-X^- stars, then a comparable energy generation rate can be had in a star with X^- number abundance fraction $Z_x/\mathrm{H} > \tau(^{10}\mathrm{C}^x)(Z_{\mathrm{lim}}/\mathrm{H})/\tau(\mathrm{CNO}) \approx 10^{-8}$ so long as Z_x/H in this star is of this order.

To be consistent with the experimental upper limit on X^- concentration in the galaxy today, $Z_x/\mathrm{H} < 10^{-25}$, the X^- abundance must have decreased at least 17 orders of magnitude over the succeeding 1.5×10^{10} yr, i.e., the X^- lifetime must be $\tau_x < 4 \times 10^8$ yr. We note that this constraint is comparable to the time scale for the primordial star formation epoch ($< 10^9$ yr).

The nucleosynthesis yield in the explosions of these X^--induced super-supernovae would be that described in the last section, notably, enhanced O/C and O/N ratios and an enhancement of the abundances of the heavy O isotopes compared to that of ^{16}O. Though it is difficult to observe isotope shifts at low abundance, it may be possible with future astronomical instruments (cf. the discussion of this point in Kajino et al. 1990).

4. SUMMARY

We have demonstrated several features of X^- particles. First, the present abundance constraints allow them to have been active in the first generation of stars. Second, their processes of nucleosynthesis would have allowed them to catalyze an extremely efficient hydrogen-burning cycle. Third, the energy generated from that hydrogen-burning cycle could have profoundly affected the constraints previously concluded for very massive and supermassive stars. Fourth, higher mass nucleosynthesis cycles would have generated small amounts of C and N, and much larger amounts of O. Furthermore, the O isotopic abundances might provide a signature of the presence of X^- particles in the first generation stars.

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